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## The forward particle production in the energy range of 1 PeV as seen with the Tibet hybrid experiment

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**Abstract:** We are now operating the 500  $m^2$  Yangbajing air-shower core (YAC-II) array near the center of the Tibet air-shower array (Tibet-III) to observe cosmic-ray chemical composition at the knee energy region since February 2011. The first step of YAC, called YAC-I, containing 16 detector units, was operated from May, 2009 to February, 2010. In this paper, we used the YAC-I and Tibet-III coincident data set obtained from May, 2009 through January, 2010 to present the electromagnetic spectrum of air shower cores at around  $10^{15}$  eV energy region. The effective live time is calculated as 100.5 days. We would like to report the comparison of our experimental data with MC model prediction in this paper.

**Keywords:** cosmic ray, hadronic interaction, air shower

## 1 Introduction

Direct measurements of the primary cosmic rays (CR) with energies higher than  $10^{15}$  eV are difficult due to their low flux and the limited detector acceptance of the on board satellite or balloon experiment. Instead, their properties are reconstructed from the measurements of the extensive air showers (EAS) they produce in the atmosphere. The reconstruction of EAS events is based on Monte Carlo hadronic interaction models of the air shower development, which are based on the knowledge obtained from the accelerator hadron-nucleus collision experiments. Since accelerator experiment can not provide all information that cosmic ray studies need, some extrapolation to higher energies and to un-reached phase space is inevitable that induces uncertainty in the explanation of AS phenomenon.

It is well known that the produced particles in the most forward region of hadronic interactions are most responsible for the AS development, and the most forward region is the dead-corner of conventional collider experiments. It is also known that the high energy particles in the AS core region are most sensitive to the forward region particle productions. Because of the advantage observing EAS cores in the high altitude, a new hybrid experiment was constructed and operated in Yangbajing, Tibet.

In present work, we report the checking of hadronic interaction models by observing EAS cores at the energy region of  $10^{15}$  eV using Yangbajing Air shower Core detectors (YAC-I) and the air-shower array (Tibet-III).

## 2 The Tibet hybrid experiment

The Tibet hybrid experiment consists of air-shower array (Tibet-III) and YAC-I. The Tibet-III array [1] consists of 733 scintillation detectors ( $0.5 \text{ m}^2$  each). Fast-timing detectors are placed with  $7.5 \text{ m}$  spacing and density detectors are placed with  $15 \text{ m}$  spacing. An event trigger signal is issued when any four-fold coincidence occurs in FT counters with each of them recording more than 0.6 particles. The primary energy of each AS event is determined by the air shower size ( $N_e$ ) which is calculated by fitting the lateral particle density distribution to the modified Nishimura-Kamata-Greisen (NKG) structure function.

YAC-I that consists of 16 EAS core detectors is shown in Fig.1 and for the brief description see [2], which has started data taking since May, 2009. YAC-I is located near the center of the Tibet-III air-shower array, operating simultaneously with Tibet-III. For the coincident events Tibet-III provides the total energy and the direction of air showers and YAC-I observes high energy electromagnetic particles in the core region.

If any one of YAC-I detectors makes a trigger signal that corresponds to at least 20 MIPs' incidence, all ADC data from all YAC-I units are recorded. Also the trigger signal is sent to DAQ system for AS array. ADC modules of YAC-I are calibrated every 4 hours. ADC pedestal values are measured every 10 minutes. Each DAQ system has GPS

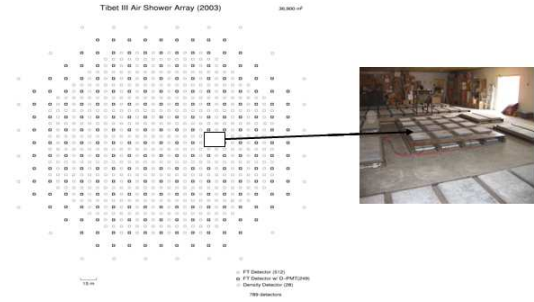


Figure 1: Schematic view of the Tibet-III air-shower array and YAC-I array.

clock module independently. The matching between YAC data and AS data is made using coincidence of GPS clocks and trigger tag to AS array. The coincidence condition of GPS is about  $1 \mu\text{s}$  [3].

In the following analysis, we present our results based on the YAC-I data and AS data.

## 3 Simulation and Analysis

A Monte Carlo simulation has been carried out on the development of EAS in the atmosphere and the response in YAC-I. The simulation code CORSIKA (version 6.204)[4] including QGSJET2 and SIBYLL2.1 hadronic interaction models are used to generate AS events. The assumed primary cosmic-ray composition in MC is based on Non-Linear Acceleration (NLA) model (about details, please see [5][2]). The fractional contents of the assumed primary cosmic-ray flux are listed in Table 1. Primaries isotropically incident at the top of the atmosphere within the zenith angles from 0 to 60 degrees are injected into the atmosphere. The minimum primary energy of this simulation is set at 1 TeV. Secondary particles are traced to the altitude of 4300 m till 300 MeV. For each simulated AS event that reaches the observational level, its core is dropped randomly onto an area of  $52.84 \text{ m} \times 52.14 \text{ m}$ , which includes the marginal space of  $25 \text{ m}$  outside the each side of detectors. MC simulation shows that the core resolution is better than  $2 \text{ m}$  if taking the  $N_b$  weighted center as the AS core. The electromagnetic showers in the lead layer induced by electrons or photons that hit any detector unit of the array are treated by a subroutine that is based on the detector simulation code EPICS (version 8.64)[6].

Normally, the following quantities of YAC are used to characterize an EAS core event: The number of shower particles hitting a detector unit is called 'burst size' ( $N_b$ ). When the burst size of a detector unit is higher than 200, this unit is defined as a 'fired' one. We also call the total burst size of all fired detector units as  $\sum N_b$ , the maximum burst size among fired detectors as  $N_b^{\text{top}}$ .

Table 1: Fractions of components in the assumed primary cosmic-ray spectrum of the NLA model.

Com.	$10^{14}$ - $10^{15}$ eV	$10^{15}$ - $10^{16}$ eV	$10^{16}$ - $10^{17}$ eV
P	26.3%	10.0%	5.0%
He	28.7 %	17.5%	11.4%
M	34.4%	50.3%	48.5%
Fe	10.6%	22.2%	35.1%

Table 2: The fraction of the components after the event selection.

Com.	$10^5 < N_e < 5 \times 10^5$	$N_e \geq 5 \times 10^5$
P	58.3%	21.3%
He	29.8%	23.4%
M	11.3%	40.8%
Fe	0.6%	14.5%

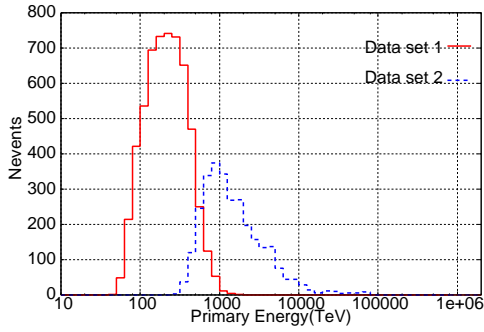


Figure 2: The distribution of primary energy of the sample of two data sets.

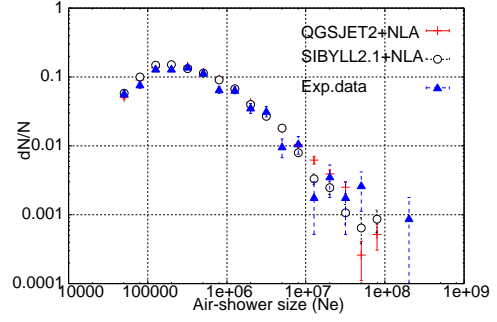
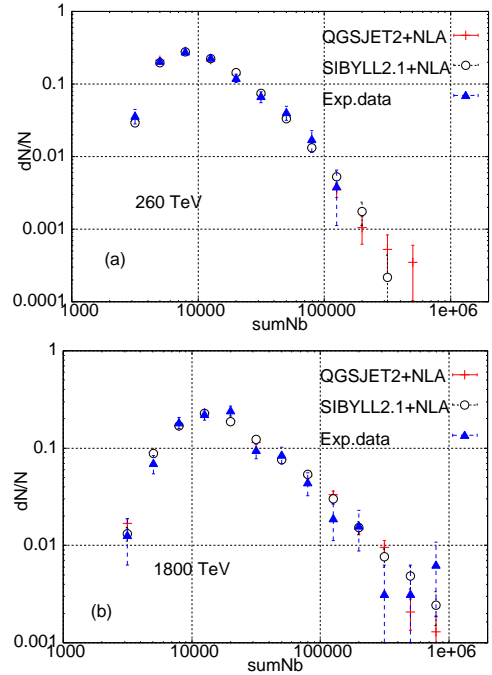
Table 3: The number of events of 2 selected samples.

$N_e$	QGSJET	SIBYLL	Expt.data
$10^5 < N_e < 5 \times 10^5$	5687	4581	523
$N_e \geq 5 \times 10^5$	3858	2888	317

We can obtain different event samples that have different average primary energy and different sample size by using different threshold of  $N_e$ . Therefore, we can see how some physics quantities change with energy simultaneously. We obtain two data sets by imposing the following conditions: (1)  $N_b \geq 200$ ,  $N_{hit} \geq 6$ ,  $N_b^{top} \geq 1500$ ,  $10^5 < N_e < 5 \times 10^5$ ;

(2)  $N_b \geq 200$ ,  $N_{hit} \geq 6$ ,  $N_b^{top} \geq 1500$ ,  $N_e \geq 5 \times 10^5$ ; Fig.2 shows the primary-energy distribution of these two data sets. The mode energy as known from the Monte Carlo is 260 TeV and 1800 TeV, respectively.

We sampled  $1.8 \times 10^{10}$  and  $1.17 \times 10^{10}$  primaries for the QGSJET2 and SIBYLL2.1 model, respectively. The number of events of two data sets selected under the above conditions can be seen from Table 3. The simulated data were analyzed in the same manner as in the procedure for the experimental data analysis. In present paper, we used the experimental data set obtained from May, 2009 through Jan-

Figure 3: The comparison of air-shower size  $N_e$  between MC and experimental data.Figure 4: The spectrum of the total burst size  $\sum N_b$  obtained by MC and experimental data at 260 TeV (a) and 1800 TeV (b) energy region, respectively.

uary, 2010. An event coincidence between AS events and YAC-I events is made by their arrival time. Deadtime correction of 12% for AS trigger system and 15% for YAC-I trigger system are taking into account. The data sample coming from successful coincidence corresponds a live time of 100.5 days. The total number of events which is selected under the above two conditions from the experimental data is also listed in Table 3.

## 4 Results and Discussion

Since our Monte Carlo simulation is started from 1 TeV, in order to normalize MC data and experimental data, we need to know the integral intensity of all particles

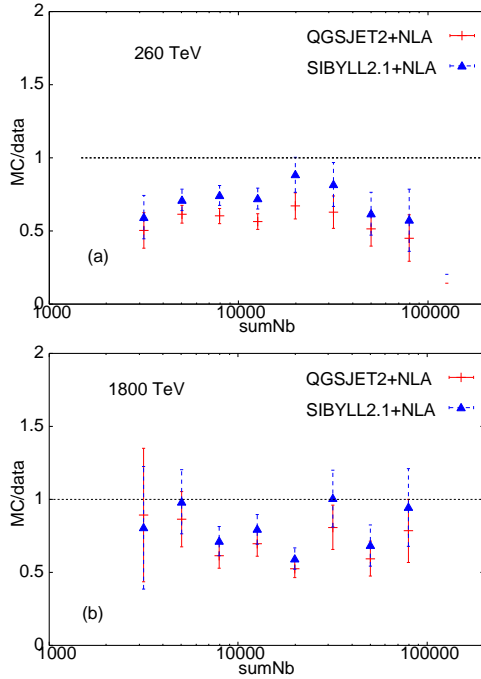


Figure 5: The flux ratio of the absolute intensities of the total burst size  $\sum N_b$  obtained by MC and experimental data at 260 TeV (a) and 1800 TeV (b) energy region, respectively.

of cosmic rays at  $E_0 \geq 1$  TeV: starting from Hörandal's spectra of each composition[7], we improve the major 8 ones (P, He, C, O, Ne, Mg, Si, and Fe) by the newest measurements [8][9][10]. The resultant integral intensity:  $I(\geq 1 \text{ TeV}) = 0.139 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  with the error  $+0.0013$ ,  $-0.0012$  coming from the error of the index of each the 8 spectra.

Fig.3 is the comparison of air-shower size ( $N_e$ ) between MC and experimental data which are normalized by number of events. It shows both MC models produce air-shower size distribution consistent with experimental data.

Fig.4 is the comparison of the total burst size  $\sum N_b$  which are normalized by number of events between MC and experimental data at 260 TeV and 1800 TeV energy region, respectively.  $\sum N_b$  should depend sensitively on the inelastic interaction cross section, the inelasticity, and particles produced in the forward region. It shows that these two hadronic interaction models have the same shape with experimental results.

Fig.5 is the flux ratio of the absolute intensities between MC and experimental data. It shows that both QGSJET2 and SIBYLL2.1 give about 40% lower flux.

## 5 Summary

The shape of the distributions of  $\sum N_b$  is consistent between the YAC-I data and simulation data in these two cases, indicating that from 260 TeV to 1800 TeV, the particle production spectrum of QGSJET2 and SIBYLL2.1 may correctly reflect the reality within our experimental systematic uncertainty of a level about 10%.

But note that, NLA composition model used a steeper He spectrum [5], our results are still affected by the composition model used, comparing with the new results from PAMELA and CREAM. Enhancing He spectrum may change the results. The bending energy of p and He spectra may also be an important factor. It is also noticed that, seen from Table 2, the 2 data samples have different composition. Therefore, at present stage, it is not simple to make a conclusion. A further study is needed and is going on.

The above results show that taking the priority of high altitude (like Yangbajing) an EAS core event sample can be obtained with high statistics by using YAC type detector, and the hadronic interaction models can be checked. YAC-II has been constructed and start data taking since August 1st, 2011, the more results will be expected.

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